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ECONOMIC REGULATION OF TARGETING BEHAVIOR IN A MULTISPECIES FISHERY

by Robert McKelvey

Resources Paper No. 75

December 1981

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Economic regulation of targeting behavior in a multi-species fishery

1. Introduction

A prominent theme in the recent literature on fisheries regulations has been the policy dichotomy between imposition of price regulation (landings taxes) and quantity regulation (transferable quotas) on the product of the individual fishing enterprise, as a means of achieving optimality relative to a social objective of economic efficiency for the fishery. It has been recognized [Scott-1979] that, under assumptions of strict determinism and full information, these policy instruments are entirely dual, but strong caveats have to be laid down regarding complications that can be expected in a real fishery.

Theoretical analyses of these questions have been based in part on the development of analytical models [Moloney-Pearse, Clark 1979] which show very clearly the nature of the duality and its basis in the shadow pricing of the unfished stocks - a result that arises formally through the machinery of the Pontryagin maximum principle.

Of course, theoretical analysis of fisheries regulation is not new: and the present-day student still can profit by re-reading some of the early studies [Scott 1962, Crutchfield], which seem now remarkably comprehensive, considering that they came so quickly after the original enunciation of Scott Gordon's common property behavioral assumptions. The early writers were very much aware that simple theorizing would be complicated in demersal fisheries by the fisherman's ability to choose among alternative fishing grounds (Gordon himself addressed this issue) and by the multispecies character of the catch. But descriptive analysis seemed inadequate to clarify the implications of these factors.

As a current instance, the increasing importance of the Northern Pacific trawl fishery has sparked a considerable discussion of limiting entry and of imposing controls on particularly vulnerable or commercially valuable groundfish species. However the discussion has gone on in the absence, still, of any precise theoretical basis. While there are some relevant modeling analyses [Huppert, Anderson], these studies emphasize multipurpose fleets rather than geographically extensive grounds. Furthermore, it seems important, as Scott [1955] pointed out a long time ago, to explicitly separate short-run and long-run considerations in the analysis.

In this article I present a model of a multi-species, geographically extended fishery, assuming that fishermen have the ability to target their effort on particular fish aggegrations (whether or not these remain in geographically fixed locales). The analysis is mainly of intra-seasonal organization of the fishery and of the efficacy of short-run regulatory controls. Analysis of long-run entry, exit, and capital investment is put aside. However, it is assumed that long range management goals require seasonal conservation of scarce and valuable species.

An example is a mixed species trawl fishery, where certain valuable species (e.g. ocean perch or petrale sole) tend to be overfished. Another is a single-species fishery in which age-classes are geographically distributed in inhomogeneous mix, and it is desired to conserve large old spawners.

The analysis is based on a simplified model, considered under idealized circumstances of certainty and perfect information. The model assumes a significant "thinning externality", linking the productive processes of the individual fishing vessels through declining fish stocks. The individual fisherman's decisions, on intensity of effort and target switching, are based on his presumed desire to maximize seasonal earnings.

In these reference conditions, the open-access common-property fishery organizes itself in a coherent and intuitively plausible way. It becomes possible in principle to modify the vessel operator's behavior to achieve a social optimum, either by imposing time-and-space-varying landings taxes, or by establishing markets in time-and-space-allocated quota rights. Additionally, license limitation (or tax) is required to achieve optimal fleet capacity in the long run.

However, optimal regulatory schemes impose unrealistic enforcement requirements upon the management agency, and thus it becomes appropriate to examine operationally simpler, although suboptimal, regimes. An obvious modification is to replace time-and-space variable taxes by constant ones, or time-and-space related species quotas by overall ones. Unfortunately these simplifications come at a price: not only do they imply suboptimal fleet management but also, in the case of temporal averaging, and because of the externalities, a shifting of the information (or risk) load unequally upon the individual fisherman. The details are spelled out below.

2. The Two-Pool Model

To simplify the discussion, let us assume that, during the season, the fish stocks are concentrated within a finite number of identifiable discrete aggregations (or "pools"), each containing a mixture of species. However, between seasons all the fish of a species mingle as a single stock, and contribute jointly to future recruitment to the pools. For the simplest modeling, we consider two pools, ($n = 1, 2$), each containing fish of two species ($m = 1, 2$), in concentrations X_n^m. It will be easy to extrapolate the analysis to handle more species and more pools.

During the season ($0 \leq t \leq T$) the substocks are assumed to decline according to

$$X_n^m(0) = R_n; \quad \frac{dX_n^m}{dt} = -[q_n^m f_n(t) + \delta_n^m]X_n^m , \qquad (2.1)$$

Here $f_n(t)$ is fishing pressure exerted on pool n during the season, q_n^m is catchability, and δ_n^m is a natural mortality rate.

The management agency imposes a conservation constraint on overall stock escapement of the first species at the end of the season:

$$X_1^1(T) + a \cdot X_2^1(T) \geq E \qquad (2.2)$$

For example, $a = 1$ if the two substocks of species X^1 are identical in their contributions to future recruitment; $a > 1$ would indicate that escapement $X_1^1(T)$ is more valuable than $X_2^1(T)$, as e.g. when nursery ground survival or natality is greater for the first substock than for the second. A similar escapement constraint might hold for the second species X^2 as well, but we may conveniently assume that X^1 is more subject to overfishing so that only this one constraint binds. Effort intensity $f_\alpha(t)$ is contributed by vessels of types $\alpha = 1, 2, \ldots, A$, of varying technological efficiency, so that total effort intensity is

$$f(t) = \sum_\alpha f_\alpha(t).$$

The fleet size (or capacity) in the current season limits the maximum effort intensity that is achievable:

$$0 \leq f_\alpha(t) \leq \varphi_\alpha \; ; \quad 0 \leq f(t) < \varphi = \sum_\alpha \varphi_\alpha$$

Furthermore, effort intensity is distributed between the pools:

$$f_\alpha(t) = f_{\alpha 1}(t) + f_{\alpha 2}(t),$$
$$f_n(t) = \sum_\alpha f_{\alpha n}(t) \text{ for } n = 1, 2.$$

Hence the pool effort intensities $f_1(t)$ and $f_2(t)$ occuring in the dynamic equations (1.1) are limited by

$$0 \leq f_1(t) + f_2(t) \leq \varphi \qquad (2.3)$$

The rate of gross revenue return per unit effort applied to pool n is dependent on the current stock levels X_n^1 and X_n^2 in that pool:

$$\gamma_n = P_n^1 q_n^1 X_n^1 + P_n^2 q_n^2 X_n^2 ,$$

(Here P_n^1 and P_n^2 are unit market prices for fish.) Since the stock levels are drawn down by the effort of all vessels, this implies a "thinning externality" connecting the production functions of the individual vessels.

We shall suppose that each vessel type fishes at a fixed operating cost C_α per unit effort intensity, and that

$$C_1 < C_2 < C_3 < \ldots < C_A ,$$

reflecting the varying technological efficiencies and opportunity costs of the vessel types. Here we shall not examine the effects of start-up costs at the beginning of the season. There may also be switching costs, reflecting mainly transportation costs in traveling between pools and to home ports, but in this article we regard these as being negligible.

3. Common Property Operation of the Fishery

In a competitive open-access situation, individual vessel owners simply compare unit operating costs C_α with current returns, and act accordingly. Let

$$\gamma(t) = \max_n \gamma_n(t)$$

be the larger return to effort between the pools. Then, for each vessel type,

$$f_\alpha = f_\alpha[\gamma] = \begin{cases} \varphi_\alpha \text{ if } \gamma > C_\alpha \\ 0 \text{ if } \gamma < C_\alpha \end{cases} \qquad (3.1)$$

The effort level is ambiguous when $\gamma = C_\alpha$. For the fleet,

$$f[\gamma] = \sum_\alpha f_\alpha(\gamma) = \sum_{\gamma > C_\alpha} \varphi_\alpha . \qquad (3.2)$$

Thus $f[\gamma]$ is a monotone increasing step-function, with ambiguous values at the points of jump: these occur where $\gamma = C_\alpha$ for some α. (See figure 1.) A limiting case has a continuum of vessel types, as shown by the smooth line; this artifice removes the ambiguities at jumps.

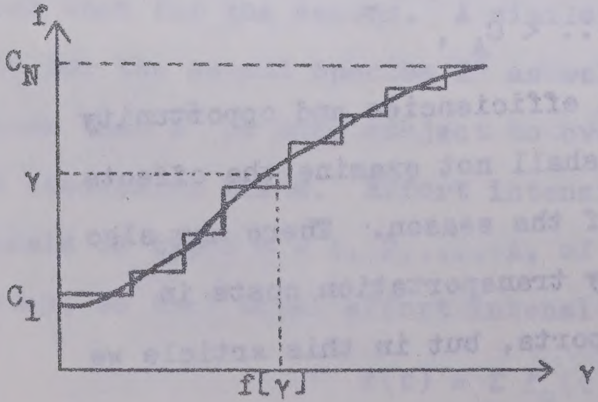

Figure 1.

Thus, the open-access fleet provides a specified level f of effort in the least-cost way. From the social perspective however, this effort level may be too high, and it may be misapplied between the pools. Let us now examine what the pool distribution will be. [Compare Clark, 1980]

We are going to assume, in this idealization, that knowledge of the current state of the pools is transmitted instantaneously through the fleet (parts of which are always probing for superior opportunities). Because switching costs are ignored, vessels switch instantaneously when it is advantageous, comparing operating costs and returns, to do so. Even though effort can be switched abruptly from pool to pool, the result, from the dynamic equations (1.1), is to draw down stock levels $X_n^m(t)$ in a continuous way. Assuming that landings prices $P_n^m(t)$, which are given exogenously, also vary continuously, it follows that $\gamma_n(t)$, the gross unit return to effort in pool n, is a continuous function of time.

Now the effort distribution can be described precisely. So long as fishing is at all profitable, if the return to effort is greater in the first pool then all effort will be concentrated there:

$$\text{if } \gamma_1 > \gamma_2 \text{ then } f_1 = f \text{ and } f_2 = 0$$

Similarly, $\quad \text{if } \gamma_1 < \gamma_2 \text{ then } f_1 = 0 \text{ and } f_2 = f$.

However, continuing concentration on a single pool (say, pool 1) will tend to draw down γ_1 relative to γ_2 until perhaps, at some time t_0,

$$\gamma_1(t_0) = \gamma_2(t_0)$$

If that should happen, effort will immediately divide between the pools in such a way as to maintain $\gamma_1(t) \equiv \gamma_2(t)$ identically. The reason is this: Should $\gamma_1(t) > \gamma_2(t)$ ever so slightly, then immediately all effort would shift back onto pool 1, tending quickly to restore the balance. The analogous shift to pool 2 would occur should $\gamma_1(t) < \gamma_2(t)$ become true. Thus the path $\gamma_1(t) \equiv \gamma_2(t)$ tends to be stable in open access.

The effort distribution necessary to maintain this balanced exploitation of pools is easy to calculate: one differentiates the identity $\gamma_1(t) \equiv \gamma_2(t)$. First, on substituting for $X'(t) = dX/dt$ from the dynamic equation (1.1),

$$\gamma_n'(t) = \sum_m P_n^{m'} q_n^m X_n^m - (q_n^m f_n + \delta_n^m) P_n^m q_n^m X_n^m$$

$$= \nu_n - \mu_n f_n, \text{ defining } \mu_n \text{ and } \nu_n.$$

Equating these, for n = 1 and 2,

$$\mu_1 f_1 - \mu_2 f_2 = \nu_1 - \nu_2$$

while

$$f_1 + f_2 = f .$$

Solving simultaneously,

$$f_1[\gamma] = \frac{(\nu_1 - \nu_2) + \mu_2 f[\gamma]}{\mu_1 + \mu_2},$$
$$f_2[\gamma] = \frac{(\nu_2 - \nu_1) + \mu_1 f[\gamma]}{\mu_1 + \mu_2}. \tag{3.3}$$

where

$$\mu_n = \sum_m P_n^m (q_n^m)^2 X_n^m \tag{3.4}$$

and

$$\nu_n = \sum_m (P_n^{m'} - \delta_n^m P_n^m) q_n^m X_n^m . \tag{3.5}$$

However, it may be physically impossible to achieve the effort distribution prescribed by equations (3.3), since the conditions must hold that

$$f_1[\gamma] \leq f[\gamma] \text{ and } f_2[\gamma] \leq f[\gamma]$$

or equivalently (since $f_1 + f_2 = f$)

$$0 \leq f_2[\gamma] \quad \text{and} \quad 0 \leq f_1[\gamma] \text{ .}$$

These require, respectively that

$$\nu_1 - \mu_1 f[\gamma] \leq \nu_2 \text{ and } \nu_2 - \mu_2 - \alpha_2 f[\gamma] \leq \nu_1 \qquad (3.6)$$

These inequalities express that, to maintain the balanced draw-down of the pools, all available effort $f[\gamma]$ applied to a single pool must be capable of compensating for differences in the change of γ in the two pools due to natural mortality and changes in price. When this ceases to be true, the effort is once again concentrated on the single more valuable pool, and balanced draw-down ceases.

It is helpful to examine a special case in detail. Suppose that there is no natural mortality ($\delta = 0$) and that prices P_n^m are constant. Introduce

$$F_n(t) = \int_0^t f_n(\tau)d\tau \text{ ,}$$

total accumulated effort applied to pool n up to time t. Then

$$X_n^m(t) = R_n^m \exp[-q_n^m F_n(t)] \text{ .}$$

Thus F_1 and F_2 can serve as state variables, replacing the four stock variables X_n^m at any time t. We find that

$$\gamma_n(F_n) = \Sigma_m P_n^m q_n^m R_n^m \exp[-q_n F_n]$$

and total accumulated fleet revenue, before cost, is

$$\Pi(\vec{F}) = \underset{nm}{\Sigma\Sigma}[P_n^m R_n^m(1 - \exp[-q_n^m F_n])$$

Hence the path of balanced decline $\gamma_1 \equiv \gamma_2$ is $\frac{\partial\pi}{\partial F_1} = \frac{\partial\pi}{\partial F_2}$, i.e. the trajectory $F(t)$ as viewed in phase space must cross the iso-revenue curves at right angles and at 45° to the axes. Effort may terminate for any of three reasons:

1) The operation becomes unprofitable: $\gamma(\vec{F}) = C_1$

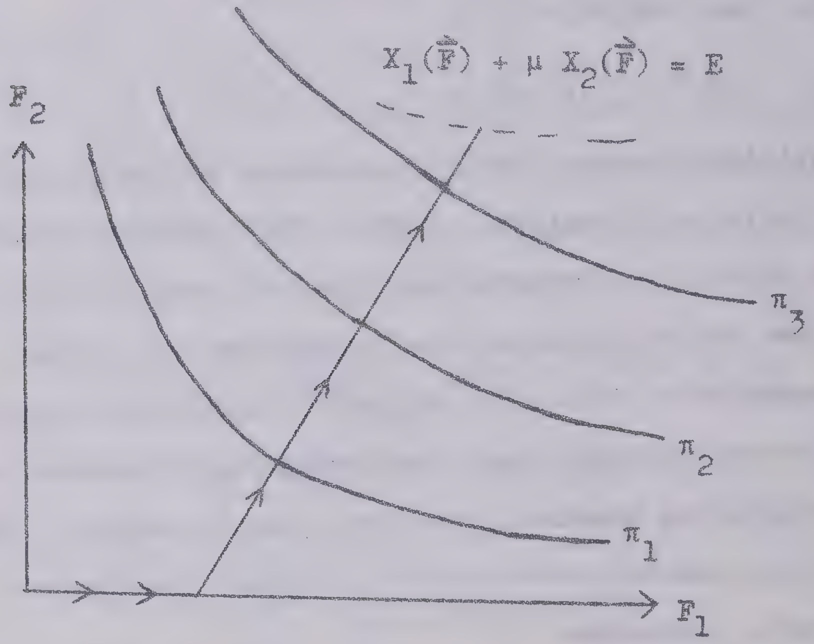

Fig. 2 Phase portrait of open access stock decline ($\delta = 0$, $P =$ constant).

2) The escapement constraint binds:

$$R_1 e^{-q_1' F_1} + a R_2 e^{-q_2' F_2} = E$$

or

3) The season ends: $t = T$.

The physical constraints of (3.2) cannot bind in this case, since $\nu_1 = \nu_2 = 0$.

4. Fleet profit optimization

As usual, one compares common property performance of the fishery with the management that would be adopted by a profit-optimizing sole owner. For the given fleet structure, least-cost effort production is achieved by vessel participation as specified in equations (3.1) and (3.2) and as diagrammed in Figure 1. The minimum cost of achieving effort intensity f is denoted C(f).

Thus, the sole owner chooses $f_1(t)$ and $f_2(t)$ to maximize

$$\int_0^T [\sum_n \gamma_n(t) f_n(t) - C(f_1 + f_2)]dt ,$$

constrained by the stock dynamics (2.1) and the escapement constraint (2.2). The Hamiltonian for this optional control problem is

$$\begin{aligned} H &= \sum_n \gamma_n f_n - C(f) - \sum_{mn}\sum \lambda_n^m (q_n^m f_n + \delta_n^m) X_n^m \\ &= \sum_n [\bar{\gamma}_n f_n - \sigma_n] - C(f) \end{aligned}$$

where $\bar{\gamma}_n = \sum_m (P_n^m - \lambda_n^m) q_n^m X_n^m , \quad \sigma_n = \sum_m \lambda_n^m \delta_n^m X_n^m ,$ (4.1)

and λ_n^m is the shadow price of the marginal unit of stock X_n^m. These shadow prices satisfy the dual dynamic equations

$$-\frac{d\lambda_n^m}{dt} = \partial H / \partial X_n^m ,$$

$$\text{i.e.} \quad \delta_n^m \lambda_n^m - \frac{d\lambda_n^m}{dt} = (P_n^m - \lambda_n^m) q_n^m f_n . \qquad (4.2)$$

The transversality conditions are

$$\lambda_2^1(T) = a\lambda_2^2(T) \geq 0 ,$$

with equality necessary when the escapement constraint is non-binding.

The dynamic equations for χ and λ yield, on differentiating (4.1), simple dynamic equations for $\bar{\gamma}_n$:

$$d\bar{\gamma}_n / dt = \nu_n , \qquad (4.3)$$

where ν_n was defined in equation (3.5). Thus whenever the prices $P_n^1(t)$ and $P_n^2(t)$ are constant or monotone decreasing, then $\bar{\gamma}_n(t)$ will be monotone decreasing as well.

The transversality conditions imply for $\bar{\gamma}_n$ that

$$\bar{\gamma}_n(T) \leq \gamma_n(T)$$

with equality necessary when the escapement constraint for X^1 is non-binding.

The effort intensity vector f_1, f_2 is to be chosen to maximize H. For a given total effort $f = f_1 + f_2$ this can be achieved:

when $\bar{\gamma}_1 > \bar{\gamma}_2$, by choosing $f_1 = f$, $f_2 = 0$

and when $\bar{\gamma}_1 < \bar{\gamma}_2$, by choosing $f_1 = 0$, $f_2 = f$.

When $\bar{\gamma}_1 = \bar{\gamma}_2$, then H depends only on f, and is independent of the decomposition into $f_1 + f_2$. In every case, putting $\bar{\gamma} = \max\limits_n \bar{\gamma}_n$,

$$H = \bar{\gamma}\, f - C(f) - \sum_n \sigma_n .$$

From this, H is maximized by choosing $f^* = f[\bar{\gamma}]$, as in fig. 1. That is, so long as $\bar{\gamma}$ lies between the fleet's unit cost extremes ($C_1 \leq \bar{\gamma} \leq C_A$), then one chooses f by the marginal rule

$$\bar{\gamma} = C'(f^*).$$

For higher returns $\bar{\gamma} > C_A$, one is constrained to the fleet's maximum effort capacity $f^* = \varphi$ and for lower returns $\bar{\gamma} < C_1$ all effort should cease: $f^* = 0$. This prescription is of course consistent with the behavior of the common property fishery, except that now gross revenue $\bar{\gamma}$ has been adjusted to include the shadow costs λ_n^m of harvesting the stocks. This is naturally what one expects on general economic principles.

What is especially interesting here is to investigate the optimal distribution of effort f^t between the pools. This question arises only when $\overline{\gamma}_1 = \overline{\gamma}_2$; otherwise all effort should be concentrated on a single pool. If $\overline{\gamma}_1 \equiv \overline{\gamma}_2$ is to hold identically over a time interval then, by (4.3), $\nu_1(t) \equiv \nu_2(t)$ identically. Differentiating ν_n in (3.5), and using the dynamic equations for X, yields

$$\nu_n' = \overline{\nu}_n - \overline{\mu}_n f_n$$

where

$$\overline{\mu}_n = \sum_m (P_n^{m'} - \delta_n^m P_n^m) q_n^m X_n^m \tag{4.4}$$

and

$$\overline{\nu}_n = \sum_m (P_n^{m''} - \delta_1 P_n^{m'}) q_n^m X_n^m - (P_n^{m'} - \delta_n^m P_n^m) q_n^m \delta_n^m X_n^m \tag{4.5}$$

Thus in order for the relation $\nu_1^1 \equiv \nu_2^1$ to persist identically over an interval of time, one must have

$$\overline{\mu}_1 f_1 - \overline{\mu}_2 f_2 = \overline{\nu}_1 - \overline{\nu}_2$$

where of course

$$f_1 + f_2 = f \, .$$

Solving simultaneously,

$$f_1^* = \frac{(\overline{\nu}_1 - \overline{\nu}_2) + \overline{\mu}_2 f^*[\overline{\gamma}]}{\overline{\mu}_1 + \overline{\mu}_2}$$

and

$$f_2^* = \frac{(\overline{\nu}_2 - \overline{\nu}_1) + \overline{\mu}_1 f^*[\overline{\gamma}]}{\overline{\mu}_1 + \overline{\mu}_2} \tag{4.6}$$

These are, of course, parallel to equations (3.3) for the common property fishery. They are limited in the same way as there by the requirement that

$$\overline{\nu}_1 - \overline{\mu}_1 f^*[\overline{\gamma}] \leq \overline{\nu}_2 \text{ and } \overline{\nu}_2 - \overline{\mu}_2 f^*[\overline{\gamma}] \leq \overline{\nu}_1 \tag{4.7}$$

Unless these relations hold, the simultaneous exploitation of pools cannot be sustained and the optimal control reverts to the exploitation of the single more profitable pool.

Equations (4.6) complete the dynamic specification of a doubly-singular optimal path. They provide the feed-back specification of $f_1{}^*$ and $f_2{}^*$ in terms of current values of X and λ needed to calculate the trajectories for X(t), λ(t) by means of equations (2.1) and (4.2).

During a time interval when all effort on pool n has been shut down so that $f_n = 0$, we observe that

$$d\lambda_n^m/dt = \delta_n^m \lambda_n^m \text{ but } d\lambda_n^m X_n^m/dt = 0.$$

i.e. unit stock value grows exponentially at the rate at which stock quantity declines by natural mortality; total stock value is constant.

A terminal interval of inactivity, $f_n(t) \equiv 0$ for $t_1 \leq t \leq T$, may come about in two ways: first, the stocks may have been drawn down to the level at which subsequent natural mortality alone will cause the escapement constraint to bind at time T. In this case the Hamiltonian is actually negative during the final time period:

$$H(t) \equiv -\lambda[\delta_1^1 X_1^1(T) + \delta_2^1 X_2^1(T)] \leq 0.$$

Alternatively, escapement does not bind, but fishing has become unprofitable at the margin: for n, m = 1, 2,

$$\lambda_n^m(t) \equiv 0, \ \gamma_n(t) = \bar{\gamma}_n(t) < C_1 \text{ on } t_1 \leq t \leq T$$

In this case $H(t) \equiv 0$ after $t = t_1$ and, by continuity of the Hamiltonian,

$$H(t_1-) = \gamma_n(t_1)f_n(t_1-) - C[f(t_1-)] = 0$$

This implies $\gamma_n(t_1-) = C[f(t_1-)]/f(t_1-) = C'[f(t_1-)]$, i.e. that the active fleet has been reduced to the single most efficient vessel type just prior to total close-down of the fishery.

The special case where prices are constant and there is no natural mortality is exceptional in the general theory. In particular $\overline{\nu}_n = \overline{\mu}_n = 0$ so that the specification (4.6) of the optimal effort distribution f_n^* fails. From (3.5), $\nu_n = 0$ so that $\overline{\gamma}_n \equiv$ constant. Thus the active fleet should be maintained at a constant size throughout the season: only those vessels for which $C_\alpha \leq \overline{\gamma}$ should fish. This reflects the obvious fact that, in the absence of natural mortality or price changes, the phasing of effort through the season is irrelevant to gross returns; only total seasonal effort F_n on each pool is important. Whatever the total effort may be, it can be achieved at lowest cost by operating the more efficient vessels steadily for the entire season. The split of total effort between pools $F_1(T) + F_2(T) = F(T)$ may be determined directly by solving the constrained optimization problem:

$$\max_{F_1, F_2} \sum_{nm}\sum P_n^m R_n^m (1 - e^{-q_n^m F_n}) - T \cdot C[(F_1 + F_2)/T]$$

consistent with

$$R_1^1 e^{-a_1^1 F_1} + aR_2^1 e^{-a_2^1 F_2} \geq E.$$

Kuhn-Tucker solution leads again to the terminal conditions $\overline{\gamma}_n(T) = C'[f(T)]$, i.e.

$$(P_n^1 - \lambda) q_n^1 R_n^1 e^{-q_n F_n} = C'[(F_1 + F_2)/T]$$

Graphically, Fig 2 applies. When escapement binds, (F_1, F_2) lies at the point of tangency between the escapement constraint curve and the appropriate iso-revenue curve.

5. Regulated open access

It is apparent that, by imposing Pigovian taxes on landings or by establishing markets for shares in landings quotas at each point in time, a management agency can in principle regulate the open access fishery to the sole-owner's optimum. To make the necessary calculations, management must know vessel costs for the fleet, market prices for fish, and the dynamics of the population biology. Notice that taxes must be levied against all fish sub-stocks, not just those subject to conservation escapement controls. (Some λ's may be negative, implying landings bonuses.) Furthermore, the tax on a given species varies with its source and the time of its harvest.

For the individual fisherman, the calculation is easier: his decision whether to fish and where is made at each instance of time based only on the current state-of-affairs: aside from current prices and taxes (or quotas) he needs to know the current biological state of the fish stocks in the pools, and the current distribution of fleet effort among pools. Beyond that he need know only his own operating costs.

Management would have to be able to monitor each vessel's location (say, by Loran records) in order to impose the correct taxes (or landings limits) appropriate to the source pool from which the fish were harvested. Alternatively, the agency might be able to identify the source of fish by the characteristic mixture of species in the landings. Should the fish in a vessel's hold represent landings from 2 or more pools, the percentages of various species present would be a convex combination of the percentages from the individual pools. Thus the agency's landings taxes could be presented as a schedule, assigning a price per thousand pounds of an aggregate landing containing a particular percentage mix. (Of course, the problems of discard or mislabeling will arise.)

Because of the enormous practical difficulties of such a management regime, it becomes appropriate to examine simpler, albeit sub optimal, management alternatives.

To begin with, let us consider a management regime in which a tax (or quota) is imposed on total landings of each species at a given time - i.e. without regard to the source pool. Plainly, putting a high tax on a valuable fish will tend to discourage exploitation of all those pools in which that fish is a dominant species, in favor of those pools where it is not.

Thus, let $\lambda^m(t)$ be specified as a landings tax (if negative, bonus) per unit harvest of species m. For simplicity we confine attention to the case where market prices P^m are constant over the season (and independent of the source pool) and where natural mortality during the season is negligible. As always, $F_n(t) = \int_0^t f_n(\tau)d\tau$ is accumulated effort applied to pool n up to time t.

The instantaneous effort f_n is obtained by comparing marginal operating costs with unit landings revenues $\tilde{\gamma}_n$ in each pool:

$$\tilde{\gamma}_n = \sum_m [P^m - \lambda^m(t)] q_n^m X_n^m = \sum_m [P^m - \lambda^m(t)] q_n^m R_n^m \exp[-q_n^m F_n].$$

With $\tilde{\gamma} = \max(\tilde{\gamma}_1, \tilde{\gamma}_2)$, the total fleet effort intensity is $f[\tilde{\gamma}]$, and when $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ are unequal, all of this effort is applied to the more profitable pool. Consider the circumstance where $\tilde{\gamma}_1 = \tilde{\gamma}_2$

over a time interval:

$$\sum_m [P^m - \lambda^m(t)] q_1^m R_1^m \exp[-q_1^m F_1] = \sum_m [P^m - \lambda^m(t)] q_2^m R_2^m \exp[-q_2^m F_2] .$$

Differentiating,

$$f_1 \sum_m [P^m - \lambda^m(t)] (q_1^m)^2 R_1^m \exp[-q_1^m F_1] = f_2 \sum_m [P^m - \lambda^m(\lambda)] (q_2^m)^2 R_2^m \exp[-q_2^m F_2].$$

This, along with $f_1 + f_2 = f[\tilde{\gamma}]$, determines f_1 and f_2 as functions of the current state variables F_1, F_2 and control variables λ_1, λ_2. Thus at any time the dynamic equations of state are

$$dF_n/dt = f_n[\gamma_1, \gamma_2, F_1, F_2, \lambda_1, \lambda_2] \qquad (5.1)$$

with right hand side a known function of state and control variables. The agency must choose controls $\lambda^n(t)$ to maximize net fleet revenue

$$\Pi[\lambda_1, \lambda_2] = \int_0^T [\sum_n \gamma_n f_n - C(f)] dt$$

$$= \sum_n \sum_m P^m R_n^m (1 - \exp[-q_n^m F_n(T)]) - \int_0^T C[f_1 + f_2] dt,$$

subject to the dynamic constraint (5.1) and the escapement constraint

$$R_1^1 \exp[-q_1^1 F_1(T)]) + a \, R_2^1 \exp[-q_2^1 F_2(T)] \geq E.$$

This is in form a standard optimal control problem.

The individual fisherman must again have specified current prices and taxes (or landings allotments), and must know current fish stocks in the pools, and effort distribution over the pools. He must know his own operating costs, but no other's. If a market bidding system is developed for shares in the total quota of landing rights, specified by species but not by pool, quota market prices will coincide with $\lambda^m(t)$. Thus, this management regime has in principle no more demanding information needs than the previous optimal scheme, but it is far easier to enforce.

The situation is somewhat different if one attempts to manage by taxes which are constant over time, or by establishing a market for shares in the overall season-long quota. Now externalities come explicitly into play. Nevertheless, it is possible to establish (at least in special cases) that the two management schemes by taxes or quota markets are equivalent under the assumption of complete information. However, they impose rather different information and computational burdens on the fishermen. In the case of taxes the fisherman is able, once again, to base his actions on the current state of the fish stocks and fleet efforts. But in the case of the quota market he must plan his strategy for the entire season, and so must know all operating costs throughout the fleet. Extrapolating to the circumstance of an uncertain environment, a tax scheme shares risk between fishermen and management agency; a quota market shifts the burden of risk toward the fisherman.

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